

SIMULATION OF LARGE-SCALE DYNAMIC SYSTEMS

Leonard Roberts*

Ames Research Center, NASA

I am honored to be the first speaker at this workshop on large-scale dynamic systems. Also, I am impressed by the scope of the workshop: "to define the classes of large-scale dynamic systems, to extract principles common to known systems, and to develop theories for the rational analysis of large-scale systems."

Certainly, the need for a comprehensive study of large-scale systems is very evident. We need only look at the state of the existing dynamic systems on which we have come to depend critically in our daily lives to conclude that this attention is needed. Our society has become increasingly dependent, almost to the point of total reliance, on a series of networks, each of which is a complex dynamic system: ground and air transportation; energy distribution; a communication system (telephone, telegraph, radio, and television); and a system of water supply, distribution, and use. As each system is stretched to the breaking point by increasing demand, they interact with each other and with yet another complex dynamic system, the natural environment.

We have seen and felt the impact of these interactions in the past year. The effect of the energy crisis, which reduced the supply of crude oil in the United States by a rather small percentage (less than 10 percent for a period of only a few months) was disproportionate relative to the size of the reduction. Road and air traffic was disrupted; communication systems, used as a substitute for travel, were overloaded; power utilities could not operate at the same efficiencies because of an unwillingness to use the more costly fuel oil, and so on. The whole system was in fact so dynamic that it went into modes of vibration that were hardly thought possible.

Nor are the dynamics of some of the proposed solutions any better understood. Substituting hydrogen for jet propulsion fuel in aircraft, for example, would entail a cryogenic ground distribution system and a completely new generation of aircraft, the designs for which are only very vaguely defined and whose impact on the air transportation system has not yet been considered. The more extensive use of coal and nuclear energy may have environmental implications that we do not fully comprehend.

Despite the awesomeness of the task, the initial approach of considering the variety of large systems we are familiar with is the correct one. In each major dynamic system, there is a fund of practical experience that represents our best source of information from which to formulate governing principles. These systems should be classified and characterized expeditiously so that individual classes of dynamic systems can be studied, thereby avoiding the pursuit of global principles that may not in fact exist.

At this point, a word of caution is due with regard to the so-called "total systems approach." This term is much used and, while it has great merit as a statement of our intention to consider all the important interactions of the system, it is also well to remember that its success depends finally

*Director, Aeronautics and Flight Systems.

on our understanding of the component parts of the system. I suggest that, as we seek to describe the dynamic character of large-scale systems, we continue to check our representation of the component parts so that the answers do not become academic as a result of unrealistic assumptions.

The tools to carry out the investigation of large-scale dynamic systems are generally available and in good shape. The theoretical tools, even for the analysis of nonlinear dynamic systems, have been developed and successfully applied in the past. With the advent of large-capacity, high-speed computers over the past decade, we can now model nonlinear systems subjected to random effects with some degree of confidence.

My remarks to this point have been rather general and I think it might be a good idea if I were to be more specific. I have spent most of my professional career in and around aeronautical activities and I hope you will forgive me for concentrating on one example of a dynamic system — air transportation. Air transportation is an important national system and it also illustrates some of the ingredients normally found in large-scale systems modeling.

I would like to consider the modeling of aircraft and air transportation at various levels of completeness and discuss the effect on computer time and speed required and the amount of "people time" required. Figure 1 shows the scope of the considerations which must be given to the total task of describing the behavior of aircraft, the traffic environment in which it operates, and the air transportation system it serves. I will describe some of the work going on in NASA in each category and then make some observations that may apply to system modeling more generally.

AIRCRAFT DYNAMICS

Aircraft synthesis, even in its simplest form, requires that the aerodynamics, structure, and propulsion of the vehicle be represented sufficiently well so that the major weight and performance tradeoff studies can be made. The primary inputs to aircraft design are represented in figure 2. The interactions between these disciplinary modules are computed and aircraft concepts are configured through a control and optimization module. The design inputs and outputs are made by use of interactive graphics so that the operator can follow the influence of the changing design inputs on the configuration.

The kind of design synthesis or vehicle description shown in table 1 can be conducted at several levels, of course, and I have summarized the computer time and "people time" involved for several levels. At the conceptual design level, this effort can be as little as 1 man year and 5 hours of computer time (on a CDC 7600) and may involve only a small number of weight elements. At the detailed design level, 100 man years of effort may be required and 1000 hours of computer design with perhaps 5000 structural elements. A fourth level of design (not shown here), final design, is usually carried out before aircraft construction and may involve an increase in effort one or two orders of magnitude over that shown for detailed design.

Thus far, I have said little about the dynamic representation of an aircraft. The dynamic modeling of aircraft has received much attention in recent years and a great deal of new understanding has resulted from the combined theoretical and experimental approach used by NASA. Figure 3 illustrates the components of a dynamic model. The primary aerodynamic and structural elements

are represented in sufficient detail that the aircraft loads, the shape deformation that results, and the consequent changes in aerodynamic characteristics can be calculated. Similarly, the disturbance function and control functions are also represented so that the total aircraft behavior can be analyzed.

Here, again, the degree of complexity of the model can vary, depending on the accuracy of the representation required. In figure 4, an aircraft is subjected to a gust. On gust penetration, the aerodynamic forces on the aircraft are changed, causing the aircraft to follow a perturbed flight path. If the aircraft is properly designed, these motions will be damped out and the aircraft will return to steady level flight – it will be dynamically stable. Three levels of description of the aircraft motion are shown in the figure.

First, if the structural flexibility is not known, the first-order aircraft motion can be found from a *rigid body* analysis. As the aircraft description is refined, a *static flexibility* model can be used which permits the interaction between structural deformation and the aerodynamics to be investigated. Finally, the *dynamic flexibility* model is required to account for the effects of structural vibration and the unsteady airloads that result.

In figure 5, I have attempted to show the effect on computer time of modeling the more complex dynamics cases. Even the rigid model requires a substantial amount of computer time (about 20 min) because of the interaction between the rigid airplane dynamics and the aerodynamics. When structural flexibility is permitted, the computation time is increased severalfold (approximately 1 hour in the case shown here) because of the airplane change of shape. Dynamic flexibility, which introduces higher frequency modes, further increases the computation time required.

The dynamic behavior of an aircraft structure, although complex, is now well understood for conventional aircraft, both theoretically and experimentally. The means for providing dynamic stability through configuration design are known and the next major step may be to incorporate active control systems that can reduce the sizes of control surface and provide load alleviation, particularly for large flexible aircraft.

TERMINAL AREA SIMULATION

We return now to the question of modeling the motion of an aircraft. The accurate depiction of aircraft motion is particularly important during approach and landing and generally for operations in the terminal area. The piloting tasks in this busy phase of flight must be properly assessed to devise safe operating procedures in the terminal airspace.

Figure 6 shows the components used in a terminal area simulation. The simulation includes (a) a piloted simulation that represents the aircraft dynamics through cockpit motion and a changing visual scene and (b) an air traffic controller who provides traffic control instructions based on information derived from the air traffic situation generated within the computer.

The *piloted simulation* includes detailed aircraft dynamics and its guidance and navigation system; also, the cockpit included a general purpose graphics display to permit variations in

information format displayed to the pilot. The simulated aircraft can be given 3-dimensional or 4-dimensional guidance or can simply respond to vectoring commands from *ground control*. Superimposed on this interaction between pilot and controller are the effects of the environment: other aircraft, wind conditions, turbulent gusts, airspace constraints due to noise, etc. Wind models, for example, have variations in direction and magnitude with altitude. The aircraft in the terminal area may have position errors as a result of inaccuracies in navigation and guidance information, so that the sensitivity of the system to error magnitudes can be determined.

The resulting output from this simulation permits an evaluation of air traffic procedures, pilot and controller workloads, the identification of worst case weather conditions, and the influence of improved aircraft capabilities.

Figures 7 and 8 show some typical results using the simulation. The problem was to investigate the impact of introducing short takeoff and landing (STOL) aircraft on the air traffic control system. Such aircraft could maneuver in restricted airspace using steep curved approach paths rather than the conventional 3° glide slope used by conventional aircraft. The purpose of the simulation was to determine whether the controller could integrate the STOL traffic with the conventional traffic on an adjacent runway.

Figure 7 shows the kind of flight paths that resulted from the controller's first attempts when he used aircraft speed control as the primary means of achieving correct time of arrival at the runway. The complex maneuvers of the aircraft arriving from the south were necessary to ensure a proper separation distance when the first aircraft failed to meet the original arrival schedule as estimated by the controller. The large speed variation available to STOL aircraft makes such an estimation more difficult.

Figure 8 shows the same arrival situation flown with the help of a 4-dimensional navigation system aboard the aircraft. The controller's task is to assign and track the runway arrival times with the assistance of a ground-based computer. The communication workload is substantially reduced and the ability of the aircraft to meet tighter spacing requirements permits a virtual decoupling of the STOL traffic from the adjacent CTOL traffic.

To study the diverse problems in terminal area research, two other types of simulations are used, in addition to the one previously described. Table 2 summarizes each type in terms of elements simulated, computer requirements, and average costs for an experiment. The first type is used to establish the feasibility of a guidance, control, or air traffic concept and is run in fast time on a general purpose computer. By virtue of its modest computer requirements and low operating expense, it is the mainstay of the systems engineer in obtaining a preliminary evaluation of a concept. Although the dynamic models simulated in it may range from simple (as for an airport capacity simulation) to very complex (as for an aircraft guidance and control system simulation), this type of simulation has one basic limitation in air transportation research: the absence of human operators as active decision-makers. In a world where man-computer, man-machine, and man-to-man interactions are increasingly more complex, this limitation is unacceptable.

The next type, which is run in real time, permits participation of human operators, namely, one controller and one pilot. It is used to evaluate a concept that has shown above-average promise in the fast time studies. The results of the study described in table 3 were obtained with this type of interactive simulation.

If a moving-base rather than a fixed-based simulator is required for the piloted simulation, the cost of running an experiment increases by almost an order of magnitude (table 2). Computer requirements also increase by a smaller factor. However, considering the high costs of building and flight testing an aircraft, the moving-base simulator is an indispensable and cost effective tool for advanced aircraft research.

AIR TRANSPORTATION SYSTEM MODELING

With an understanding of the operational modes and constraints in the terminal airspace, one can take a broader look at the overall air transportation system model. Here the interest is in finding what influences the growth of air transportation. Clearly, such factors as demand, operating economics, and environmental constraints come into play. Figure 9 displays the major elements in the model. At the left is the model of the transportation system with its major components, the arena, the traveler, and the various travel modes including the automobile, airplane, rail, and bus. Each component can be modeled in various ways, ranging from the very simple to the very sophisticated. The next block represents the analysis phase of the transportation system. Although the analysis can yield a variety of results, interest here has been centered on the air mode performance and, in particular, on the criteria of merit shown on the right, namely, demand, economics, and environmental impact.

The demand for air transportation is best measured in terms of the number of passengers the system will attract and is of obvious importance if the system is to serve a useful purpose. The economics is readily measured in terms of return on investment. The environmental criteria would generally consist of several components, but here they are limited to one – the noise impact on the community surrounding the airport.

The remainder of the figure is concerned with optimization. The three figures of merit shown are used as feedbacks to implement an optimization procedure (as indicated at the bottom) in which the variable part of the air transportation system is to be chosen to achieve the desired objective – to maximize the number of passengers carried with a constraint on the investment return and noise impact.

The part of the analysis concerned with demand is the most complex and places the most severe requirements on the computer. Figure 10 illustrates the components in the demand analysis, generally known as a modal split analysis, which determines the division of travel demand among the competing modes.

The heart of the analysis is the modeling of the transportation system components: the arena, the traveler, and the travel modes. The first element, consisting of the origin and destination regions in the arena, is modeled by subdividing the regions into zones as indicated to reflect certain similarities of the population and their spatial distribution. For this purpose, the modeling includes data on the zonal boundaries, population, income distribution, number of hotels, travel demand as a function of business or nonbusiness trips and resident or nonresident traveler, time value distribution, and local travel functions. The second element, the traveler, is modeled to represent the differences between travelers within each zone. Some of the characteristics that are modeled include

the exact origin and destination within a zone, the trip purpose, desired departure time, sensitivity to frequency of service, car ownership, trip duration, party size, time value, and modal preference factors. Modeling of the third element, the travel modes, is more straightforward and includes such factors as trip cost, trip time, service frequency capacity, noise, investment required, and operating costs.

With this data base, the modal split analysis utilizes a Monte Carlo technique that selects from particular locations within zones an individual traveler whose characteristics are determined from distribution functions. The analysis examines the competitive situation between the various combinations of travel modes which could be used between the origin and destination points as indicated in the figure. The least cost alternative is determined and it is assumed that the traveler would utilize this alternative. This process is repeated for a large number of travelers and reliable statistics on the modal split are determined. In this way, the number of travelers attracted to each of the modes shown is determined.

The methodology for determining community noise impact has its greatest impact on the computer software requirements. This methodology is illustrated in figure 11 by a series of overlays. First is shown a photograph of a typical airport and the surrounding area. To determine the noise impact of aircraft operations at this airport, it was necessary to develop a land-use model for graphically describing land uses around the airport. Such a model is shown by the first overlay on which the surrounding area is categorized into residential, planned residential, and commercial or manufacturing (as indicated by the coded areas). Each of the irregularly shaped areas corresponds to a different land value. A computer model stores the geometry of these areas and the corresponding land values in dollars per unit area. The second overlay shows the noise contours generated by a mix of proposed CTOL aircraft.

Figure 12 shows two contours for NEF 30 and 35 which would result for the assumed mix of aircraft operating on takeoff and landing patterns shown. These NEF (noise exposure forecast) contours are generated by a computer program in which are combined noise source data, noise propagation, laws, and three-dimensional aircraft position data.

The noise impact is determined by combining the NEF contours with the stored land-use model; by means of a matrix comparison technique, intersections are located between contours and land parcels. By use of land value data stored in the computer, the dollar value of the impacted areas can be determined and used as a basis for determining buffer zone costs in terms of land acquisition or possibly for use in considering land-use changes.

With this kind of computer simulation, the economic viability and environmental impact of introducing a new transportation mode into a given arena can be determined. Clearly, this approach has a much broader application than to air transportation; conceivably, it could be adapted to ascertain the merits of introducing competing forms of energy (electric power vs. natural gas, for example) or to analyze the value of introducing a new water allocation program or a new communication system.

CONCLUDING REMARKS

My remarks have been concerned primarily with aircraft and air transportation whereas the interests of this workshop are in a much broader range of dynamic systems problems.

Let me conclude by suggesting some rules we have learned the hard way in aircraft and air traffic system analysis, which may be applicable more generally to the treatment of large dynamics systems.

- Define a hierarchy of models so that the problems to be studied can be compartmentalized and uncoupled to the extent that is realistically possible.
- Distill and simplify results at each level before proceeding to limit the complexity and reduce the cycle time of computation.
- Wherever possible, and particularly where complex physical phenomena are involved, check experimentally the validity of the results.
- If the judgment of a human controller of the system is critical, provide for his participation through simulation.
- Anticipate and incorporate major system tradeoff parameters early in the formation of the system definition (e.g., demand vs. capacity vs. environmental factors).

From the agenda of presentations to follow, I know there will be a great deal of interdisciplinary interaction of ideas. Much benefit will accrue from this and I can only encourage your attempt to formalize the principles that may govern the behavior of large-scale systems.

TABLE 1.— DEFINITION OF DESIGN LEVELS

	Conceptual	Preliminary	Detailed
Resources People time Computer time*	1-2 man years 2-5 hr	7-33 man years 75-100 hr	100-200 man years 1000+ hr
Complexity Aerodynamic elements Structural elements Weight elements	4 4 25	200 200 25-50	600 5000 50+

*CDC 7600

TABLE 2.— TYPES OF TERMINAL AREA SIMULATIONS

Type	Simulated elements	Application	Computer size, megabit	Cost thousands of dollars
Fast time (concept feasibility)	Aircraft dynamics, synthetic traffic	Guidance and control, capacity, delays	1	1
Real time (concept selection and evaluation)	Fixed-base simulator, pilot, single controller, synthetic traffic	Man-computer and pilot-computer interface	2	6
	Moving base simulator, pilot, single controller, synthetic traffic	As above plus pilot workload and handling qualities	4	40
Real time (detailed design)	Several controllers, real and pseudopilots,	Procedures for medium density hub	8	200
	Several controllers, real and pseudopilots, models of automated systems	Procedures for major hub	10-20 (ILLIAC?)	300-600

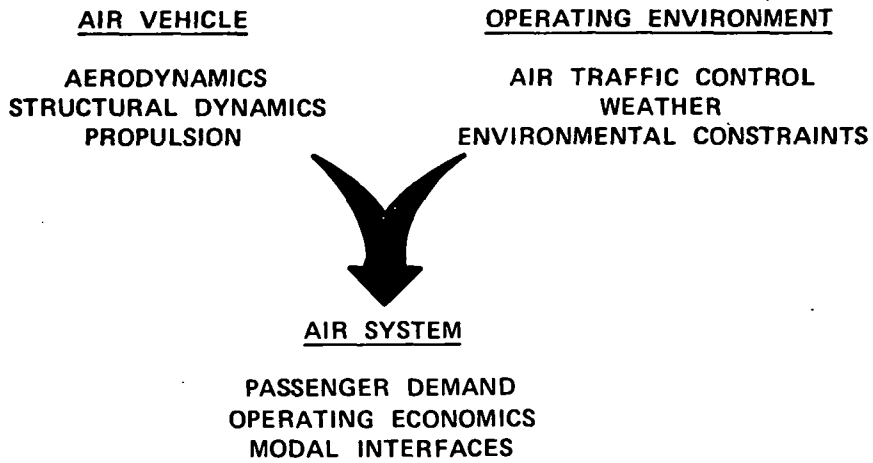


Figure 1.—Air transportation as a system.

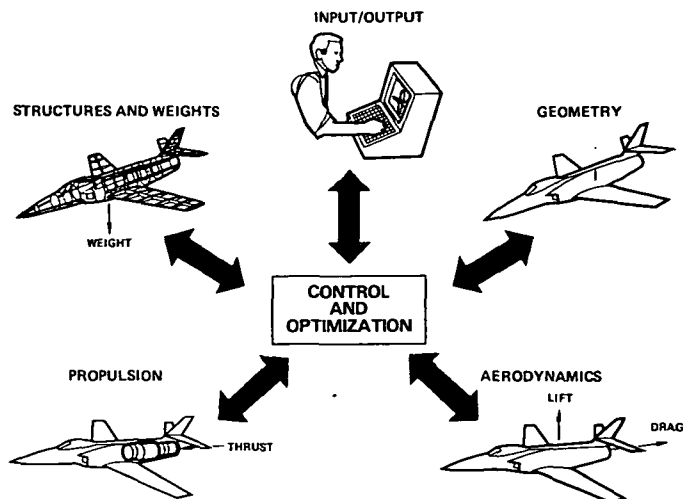


Figure 2.—Aircraft synthesis program.

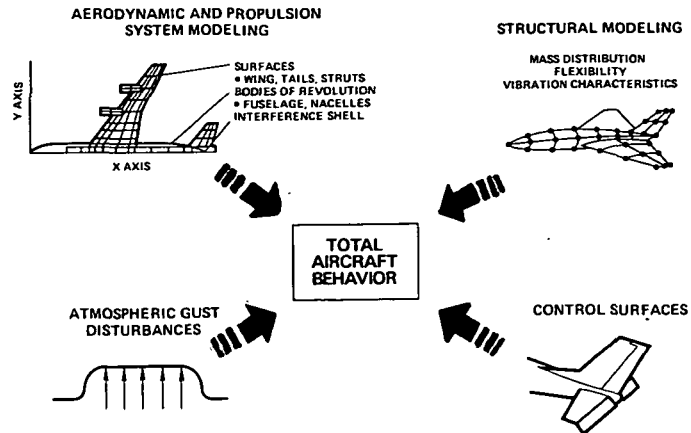


Figure 3.—Flight dynamics modeling of an aircraft system.

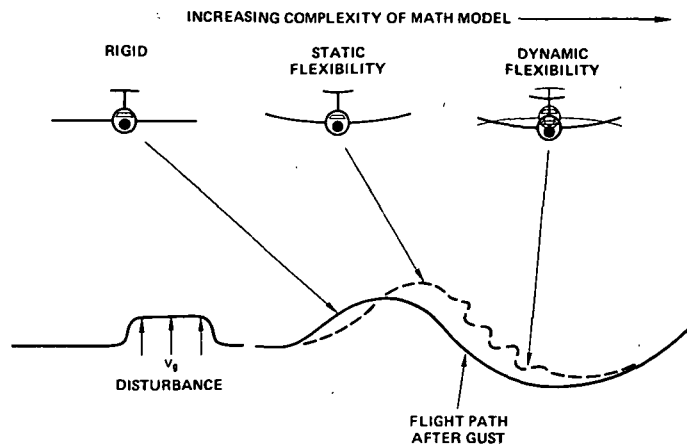


Figure 4.—Aircraft behavior models.

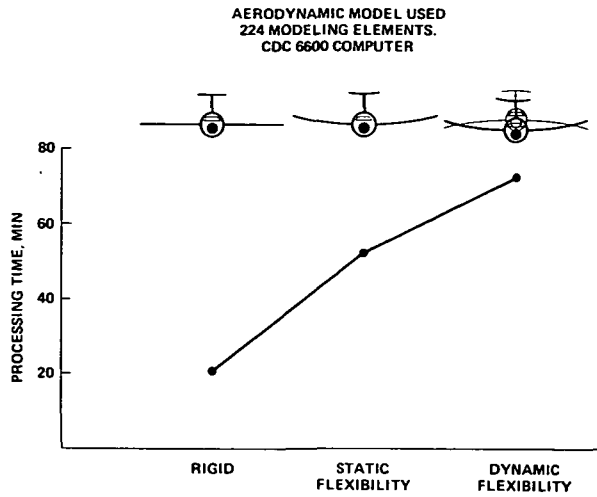


Figure 5.—Computer execution times.

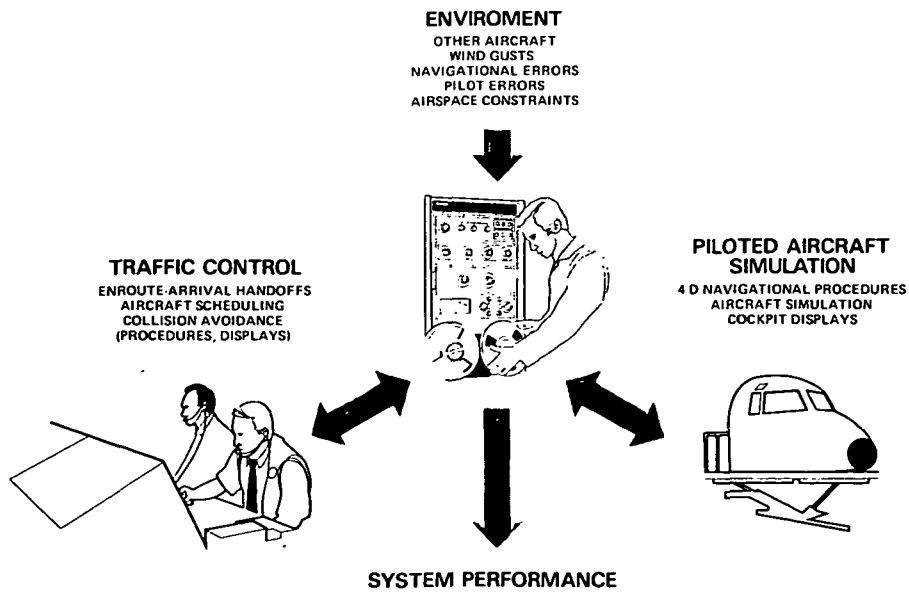
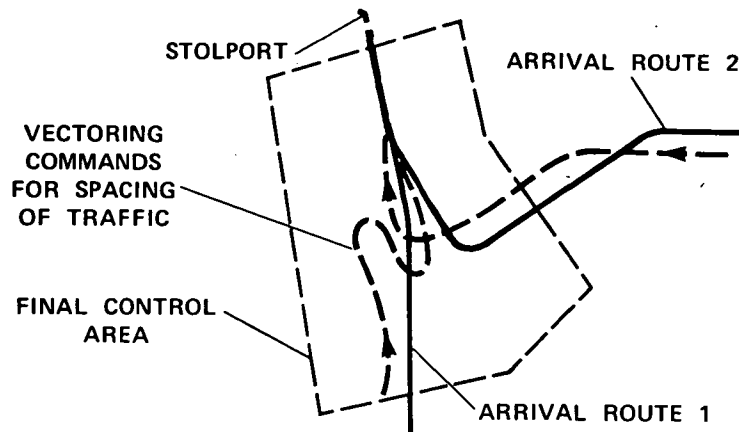
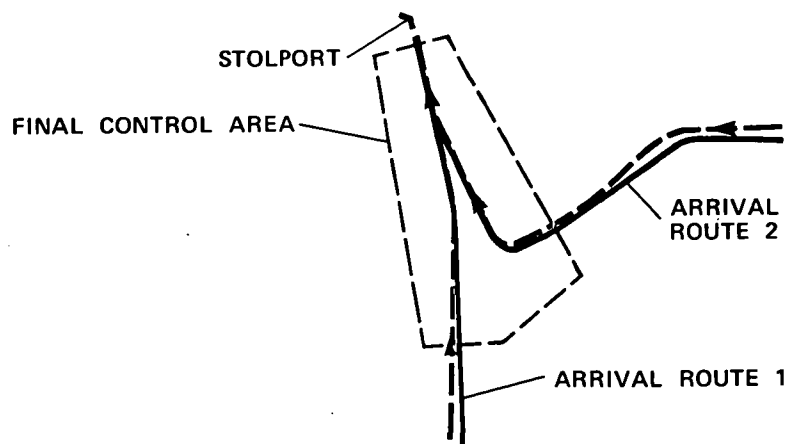


Figure 6.—Interactive terminal area simulation.



- HIGH PILOT AND CONTROLLER WORKLOAD
- LARGE TRACK ERRORS
- DELAYS

Figure 7.—Simulation results (present operating procedures for sequencing and spacing).



- REDUCED COMMUNICATIONS WORKLOAD
- INCREASED CAPACITY
- REDUCED DELAY AND FUEL CONSUMPTION

Figure 8.—Simulation results (on-board 4D navigation with computer-assisted sequencing).

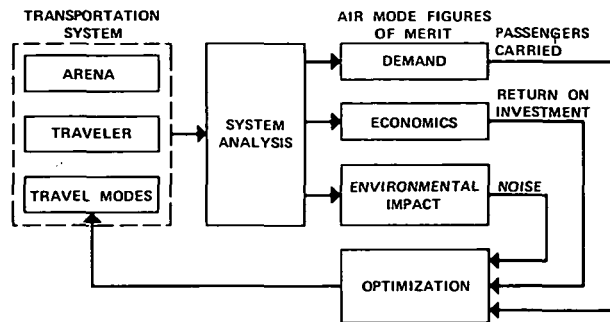


Figure 9.—Transportation system analysis.

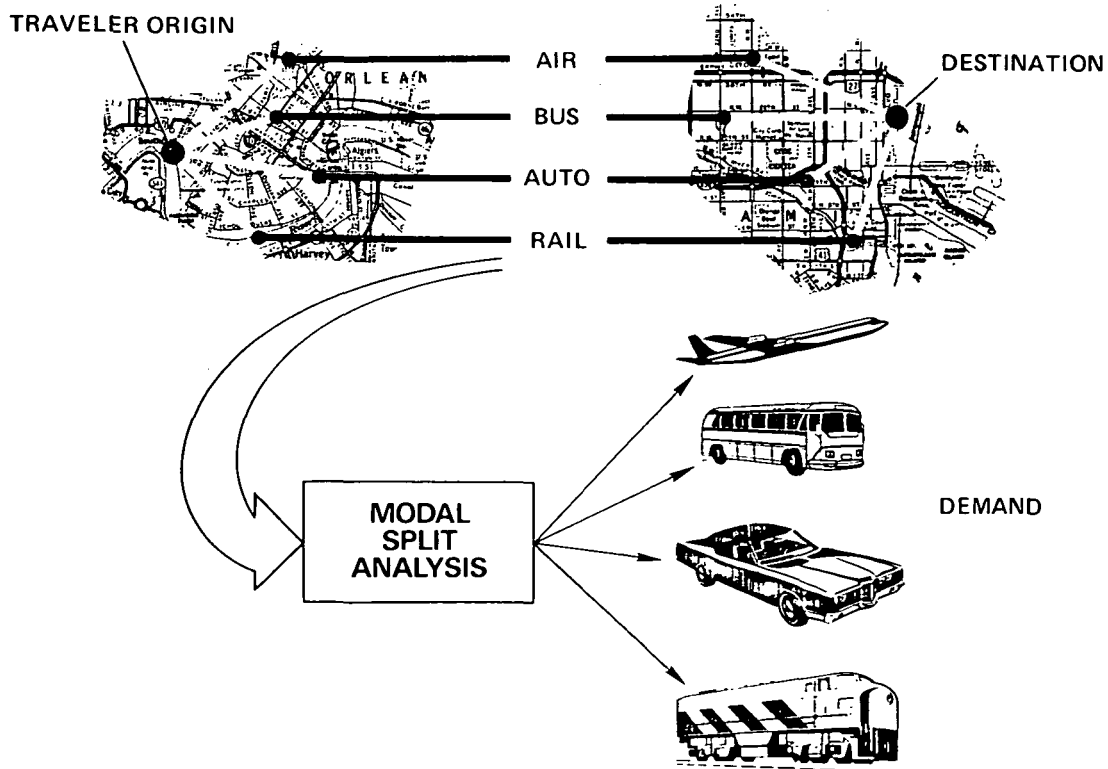


Figure 10.—Demand methodology.



Figure 11.—Typical executive airport vicinity.

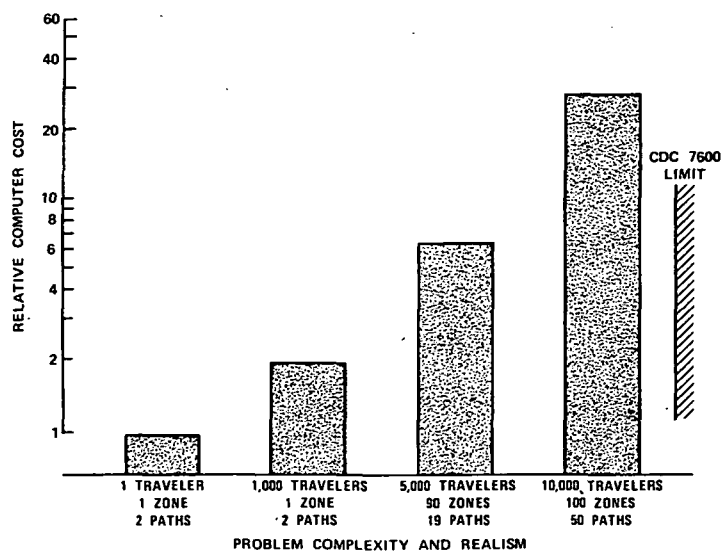


Figure 12.—Computer requirements (Monte Carlo techniques).